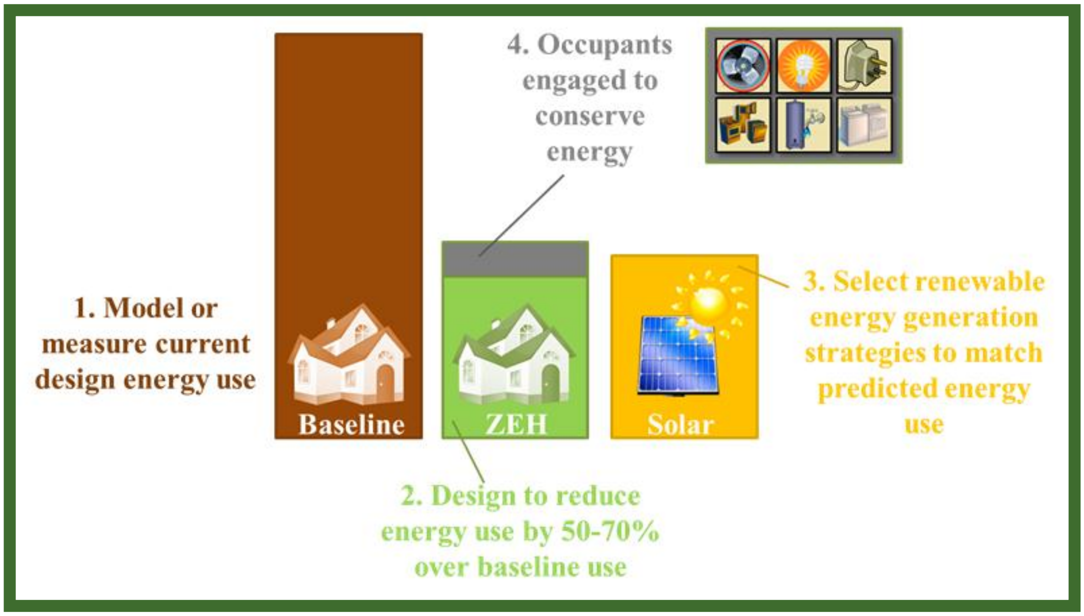
ESTCP
Cost and Performance Report

(EW-200814)



Zero Energy Housing for Military Installations

July 2013

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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ACRONYMS AND ABBREVIATIONS

BLCC	Building Life-Cycle Cost Program
Btu	British thermal unit
CFM	cubic feet per minute
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
COE	Corps of Engineers (U.S. Army)
CTC	Concurrent Technologies Corporation
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EO	Executive Order
ERV	energy recovery ventilator
ESTCP	Environmental Security Technology Certification Program
FEMP	Federal Energy Management Program
FY	fiscal year
GHG	greenhouse gas
GSHP	ground source heat pump
GTMO	Guantanamo Bay
HERS	Home Energy Rating System
HVAC	heating, ventilation, and air-conditioning
JNCO	Junior Non-Commissioned Officer
kBtu	thousand Btu
kWh	kilowatt-hour
LCC	life-cycle cost
LCCA	life-cycle cost analysis
LEED	Leadership in Energy and Environmental Design
m^2	square meter
MARR	minimum acceptable rate of return
NAHB-RC	National Association of Home Builders Research Center
NASA	National Aeronautics and Space Administration
NDCEE	National Defense Center for Energy and Environment
NIST	National Institute of Standards and Technology

ACRONYMS AND ABBREVIATIONS (continued)

NPV	net present value
O&M	operations and maintenance
PPV	public-private venture
PV	photovoltaic
RCI	U.S. Army's Residential Communities Initiative
RECS	Residential Energy Consumption Survey
SERDP	Strategic Environmental Research and Development Program
SNCO	Senior Non-Commissioned Officer
TED	The Energy Detective
USEPA	U.S. Environmental Protection Agency
USGBC	U.S. Green Building Council
ZEH	zero energy home

ACKNOWLEDGEMENTS

Funding for this demonstration project was provided by the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP). This project included many teams throughout the design, construction and performance measurement phases. Manette Messenger, retired from the U.S. Army Installation Command Southeast, was the initial leader of the project team. It was through her vision the teams came together to successfully implement the project. Heidi Kaltenhauser of Concurrent Technologies Corporation (CTC) and National Defense Center for Environment and Energy (NDCEE) were involved with the project from the beginning and a key contributor to the design, performance measurement, and life-cycle cost (LCC) analysis aspects of the project. The Pacific Northwest National Laboratory led the performance measurement and analysis aspects of the project. The project team wants to acknowledge the families that were willing to participate in the demonstration project along with the design and operation teams at Fort Campbell: Campbell Crossing, LLC (formerly Fort Campbell Family Housing, LLC), Lend Lease (formerly Actus Lend Lease), National Association of Home Builders Research Center (NAHB-RC), and Luckett & Farley.

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EXECUTIVE SUMMARY

This project evaluated the design approach and operational performance of two zero energy home (ZEH) units compared to two typically designed (baseline) housing units. Net zero energy homes generate as much electricity as they consume from the grid through a combination of: (1) energy efficient design, (2) energy generation, typically with renewable energy sources, and (3) energy conservation practices by the homeowners. The benefits of ZEHs to the U.S. Department of Defense (DoD) are lower energy costs, increased energy security, and decreased pollution from energy production and use.

One net zero energy duplex consisting of two housing units was designed and constructed in the Woodlands subdivision at Fort Campbell, Kentucky, next to a baseline duplex designed and constructed according to the standard housing design in this neighborhood. These housing units were the same size, floor plan, and orientation, and housed families with similar characteristics to minimize differences between the housing units. The ZEH design included high levels of insulation, high performance windows, a ground source heat pump, an energy recovery ventilator, and low flow water fixtures. Renewable energy systems were photovoltaic (PV) panels located on the metal roof and solar hot water heating.

Performance monitoring of all four housing units was completed to compare the energy, water, operations, occupant satisfaction, and life-cycle cost of the ZEHs compared to the baseline housing units. A monitoring system was selected, installed, and calibrated to collect data from 50 monitoring points within each home. Performance was monitored for 17 months; one year of data (January 2011 through December 2011) was used for final data analysis and results. Whole-house energy use of all four housing units was also compared to similar homes at Fort Campbell (referred to as the Woodlands community), and national averages.

The ZEH and baseline home occupants were given an orientation prior to moving into the housing units to familiarize them with the unique features of the units and the project. Tips describing how to reduce energy were provided to the occupants during this orientation. Real time energy feedback devices were placed in the housing units, and detailed monthly energy reports were provided to the occupants to inform them of opportunities for improvement. Monthly phone calls were held with the occupants to receive and provide feedback, and validate any unusual data observations (e.g., lower energy usage because occupants were on vacation).

Occupant engagement contributed to 15% less energy use in the baseline homes compared to the average home in Woodlands community. The ZEHs used on average 24% less energy than the baseline units, but did not achieve net zero energy over the study period. Figure 1 summarizes the monthly energy performance of the Woodlands typical home, the average baseline home, and the ZEHs. The average solar production for the ZEHs is also shown.

The ZEH unit used 51% less water per person than the baseline unit. Both the ZEH units and the baseline units had approximately the same level of emergency maintenance needs, but technologies in the ZEH units required more preventative maintenance than the baseline units. Multiple life-cycle cost (LCC) scenarios were completed, but no scenario was LCC effective for this location for a variety of reasons including low energy costs and interest paid on the capital investment loan.

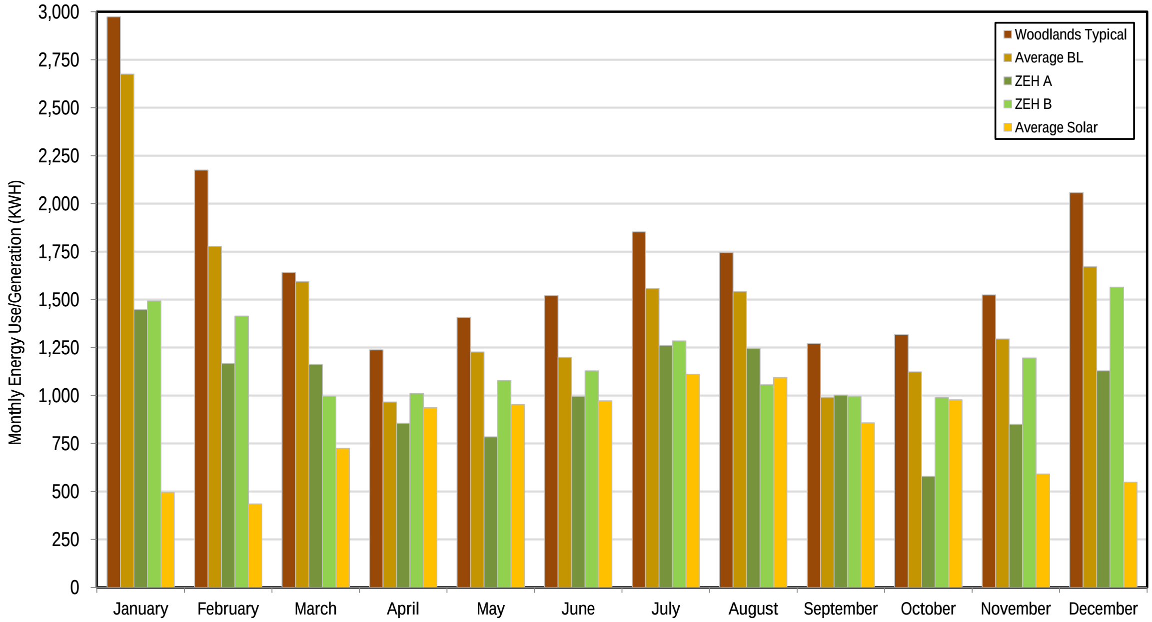

Figure 1. Monthly energy use summary.

Findings from this project included:

- Feedback devices (real-time or monthly) appear to lower energy use. Occupants found that the real time feedbacks devices were effective in helping them use less energy and water.
- Achieving net zero energy may have been possible with more than one year's data to help occupants and maintenance staff better understand and use the systems in the housing units.
- Modeling assumptions may not reflect actual building characteristics and use, which can affect the ability to design for net zero energy.
- Cost-effective ZEHs are difficult to achieve, and are most likely to be cost effective in areas where energy costs are high and renewable resources are plentiful (e.g., California).
- Incorporating a more energy efficient envelope was the least costly design change for this duplex (compared to ground source heat pumps, solar hot water systems, or solar panels).
- Specialized maintenance costs can impact the cost effectiveness of a project.

Lessons learned from this project have been shared at various industry and DoD conferences and meetings. The Environmental Security Technology Certification Program (ESTCP) team has also provided assistance to other installations requesting more information on ZEH design and monitoring approaches. Lend Lease, the Fort Campbell family housing property manager, plans to apply selected lessons learned to the 38,000 homes they manage for the DoD and the 145,000 homes they manage worldwide. Lessons learned may also be applicable for other building types such as barracks, offices, or others.

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1.0 INTRODUCTION

The Zero Energy Housing for Military Installations Environmental Security Technology Certification Program (ESTCP) project measured and compared the performance of net zero energy designed homes to typically designed homes (baseline homes). The project team tracked and provided input to the design; however, the emphasis of the project was on measuring the energy and water use of the housing units at Fort Campbell.

Energy use of the zero energy homes (ZEH) was compared to the energy use of the baseline homes. Energy use of both the ZEH and the baseline homes was compared to the average energy use of the surrounding homes in the neighborhood, called the Woodlands. Water use, operations and maintenance (O&M), energy costs, occupant comfort, and greenhouse gas (GHG) emissions were also evaluated. Table 1 shows the project timeline from design through performance measurement.

Table 1. Project timeline.

	Phase	Dates
ZEH Design	Initial design and modeling	July 2008-August 2008
	Design charrette	August 2008
	Design and modeling	August 2008-January 2009
	Construction	March 2009-October 2010
	Occupant selection	August-September 2010
	Home Energy Rating	October 2010
Performance Measurement	Monitoring system installation and calibration	September-October 2010
	Occupant orientation and engagement	October 2010-March 2012
	Families move into the housing units	October 2010
	Data collection, normalization, and comparisons	October 2010-February 2012
	Data analysis conducted and final report written	March 2012-September 2012

1.1 BACKGROUND

Residential homes use more than 20% of the energy consumed in the United States (Department of Energy [DOE], 2011). With current construction methods, buildings account for 54% of sulfur dioxide emissions, 17% of nitrous oxide emissions, and 40% of CO_2 emissions (DOE, 2011). This project evaluated the performance of two net ZEHs at Fort Campbell, Kentucky. Net ZEHs generate as much electricity as they consume from the grid through a combination of: (1) energy efficient design, (2) energy generation, typically with renewable energy sources, and (3) energy conservation practices by the homeowners. The issues validated were actual performance and cost compared to industry baselines and two conventional homes in the same subdivision. The benefits of ZEHs to the U.S. Department of Defense (DoD) are lower energy costs, increased energy security, and decreased pollution from energy production and use.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this project was to evaluate the performance of the design and construction of the Fort Campbell ZEHs. The project included two duplexes within a Fort Campbell residential development known as the Woodlands. Energy consumption, environmental impact, operational effectiveness, and life-cycle costs (LCC) were measured for two typically designed housing units (one duplex) and two ZEHs (one duplex).

There were two key components to this project. The first was to provide insight on integrated design strategies. To achieve this, sustainable design objectives were incorporated into the design of the ZEH units. The intent of this project was to incorporate necessary design requirements for zero energy without significantly modifying the floor plans and/or exterior elevations of the buildings. This approach took advantage of established costs and scheduling requirements available and allowed for a comparison to all of the duplexes in the Woodlands community, and maintained housing equity among the Fort Campbell residents. A computer simulation was conducted to model the energy and water use of the ZEH design and the baseline units; energy modeling and national standards were used to assess the design.

The second project component was to evaluate the measured performance of the ZEH units and compare it to multiple baselines. Those baselines included the following:

- Measured performance of the typically designed units (referred to as the baseline units)
- Average measured performance of similar Woodlands residences in 2011
- Average measured performance of similar Fort Campbell residences in 2008
- National standards (Residential Energy Consumption Survey [RECS])
- Expected performance based on the design estimates for the ZEH and the baseline units

1.3 REGULATORY DRIVERS

Executive Order (EO) 13423 set goals to improve energy efficiency and reduce GHG emissions through reduction of energy intensity by 3% annually through the end of fiscal year (FY) 2015, or 30% by the end of FY 2015, relative to a 2003 baseline. EO 13514 expands on the energy reduction and environmental performance requirements of EO 13423 by setting a goal for each federal agency to establish an integrated strategy towards sustainability and make the reduction of GHG emissions a priority. The Energy Policy Act of 2005 specifically encourages the use of energy efficient buildings as a means for reducing GHG emissions. The Energy Independence and Security Act of 2007 requires that new federal buildings decrease their consumption of fossil fuels by 55% by 2010 and 100% by 2030. Recently, DoD set goals in their Strategic Sustainability Performance Plan to reduce scope one and two GHG emissions by 34%, and indirect scope three emissions by 13.5%.

ZEH contributes to achieving the goals outlined in these document through decreased energy consumption, and therefore decreased GHG emissions.

2.0 TECHNOLOGY DESCRIPTION

The technology demonstrated has two components: (1) design and operation of a ZEH, and (2) performance measurement to evaluate the ZEH design. These two components are described in more detail in the following sections.

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

ZEHs are designed to generate as much energy as they use over the course of a year. The design process uses extensive energy modeling to identify the optimal mix of building systems to obtain a 50-70% reduction in energy use over a typical residential building. Renewable energy systems are used to provide the remaining energy use. Occupants are encouraged to operate the home in ways that support the net zero energy goal, and must be actively engaged in pursuing the energy goals for the home to achieve net zero energy. Figure 2 provides an overview of the zero energy methodology.

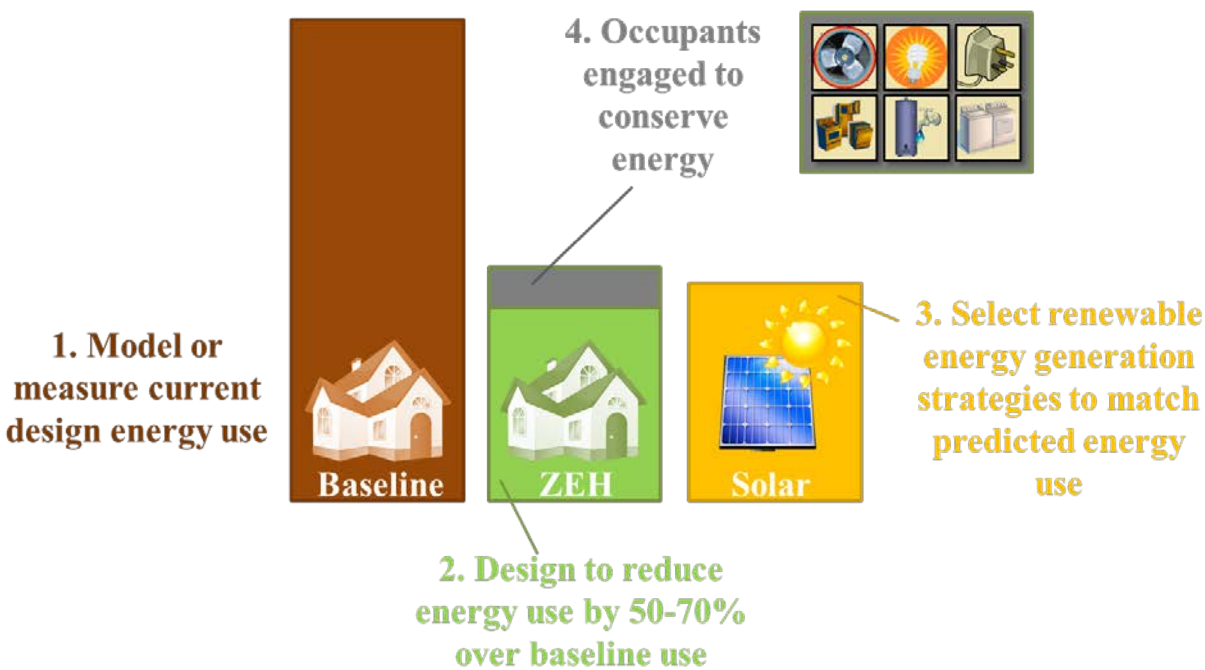

Figure 2. Zero energy methodology.

Whole building performance measurement evaluates existing sustainably designed buildings by documenting operational data to determine if the buildings perform as intended. To gather useful information, the operational data needs to be:

- measured, not modeled;
- representative of sustainable design principles, not just individual design strategies such as energy efficiency; and

- translatable into cost values that could be shared with the financial decision makers to demonstrate performance in their language.

The operational data provide basic information about a building's comparative performance with respect to sustainable design. The metrics collected include energy, water, maintenance, waste generation, indoor environmental quality, and transportation. The method used is defined in detail in the *Whole Building Cost and Performance Measurement: Data Collection Protocol Revision 2* (Fowler, et al., 2009).

2.2 ADVANTAGES AND LIMITATIONS OF THE ECHNOLOGY/METHODOLOGY

ZEHs have the following advantages:

- Reduced energy consumption: The design and optimum operation of a ZEH results in lower energy use than typical housing units. The actual reduction and associated cost savings is dependent on the building design and how it is operated by the occupants.
- Cost predictability: Because ZEHs provide a large percentage of a home's electricity needs with renewable sources, price risks are significantly mitigated. Given the impact of seasonal and daily weather on the long-term cost of electric energy, the volatility of the electric market can dwarf that of other commodities (corn, gold, pork bellies, etc.) that are traded in an open market.
- Energy security: ZEHs increase energy security, and mitigate mission risks posed by unpredictable availability of energy. On-site generation provides an essential redundancy to power provided by the local electric utility. ZEHs will have a dual source of energy providing power when their systems are down (e.g., occasional maintenance) or when there is a failure of the local electric utility.
- Operational benefits: Increased building occupant comfort translates into increased family and soldier readiness. Increased DoD ability to operate in energy-shortage and high-energy-cost areas will ensure that major training bases remain affordable and available for soldier training.
- Reduced air emissions: Based on source energy and emission factors developed by Deru and Torcellini (2007), 70% energy savings for just one home at Fort Campbell could reduce total emissions by about 50,591 pounds per year, thus reducing CO_2 emissions by about 44,406 pounds per year.

The advantages of performance measurement include:

- Data can be used to inform decision makers and stakeholders regarding the life cycle costs and benefits of sustainably designed buildings.
- Proactive identification of operational issues that, when addressed, can improve building performance, reduce operational costs, and reduce occupant complaints.
- Data can reveal opportunities to inform future building designs, as to which design and operations strategies were most effective in reducing energy and water use, while maintaining occupant comfort.

ZEHs have the following limitations:

- The high cost of on-site renewable energy generation, such as photovoltaics (PV), is only LCC effective in locations that have higher-than-average utility rates.
- Occupants must be actively engaged in pursuing the energy goals for the home to achieve net zero energy.
- Atypical weather could impact the quantity of energy used and/or generated.
- Less than optimal construction practices, equipment installation, and/or equipment maintenance can impact the potential of a ZEH operating as expected.

Performance measurement has the following limitations:

- Measurement and analysis can be expensive and time consuming, depending on the level of detail desired. Detailed measurement and analysis is needed to answer specific performance questions. Performance measurement can be limited by the amount and type of data available for analysis. Additional metering equipment may be required, which adds to the cost and can make the analysis difficult to replicate on a large scale.
- Data analysis, data management, and building systems knowledge are necessary to effectively use the performance measurement data.
- Monitoring systems can fail causing data gaps that need to be addressed during data analysis.

DoD provides more than 300,000 family housing units, which combined use 11 trillion British thermal units (Btu) of electrical energy annually. In FY 2006 alone, this energy cost $254 million and represented 11% of DoD's total facility electrical use. Much of this electricity was generated by coal-fired plants, which are responsible for generating 40% of U.S. mercury emissions. Electric energy used in DoD homes not only contributes to environmental challenges, but also creates serious energy security problems for our military installations. A 100% dependence on energy produced by finite resources and stressed electric power grids represents vulnerability in maintaining troop readiness. Potential DoD users of the ZEH findings include other Residential Communities Initiative partnerships, which represent approximately 160,000 homes. In addition, Lend Lease plans to apply selected lessons learned to the 38,000 homes they manage for the DoD and the 145,000 homes they manage worldwide.

3.0 PERFORMANCE OBJECTIVES

Table 2 lists 14 specific performance objectives. The Design and Measured objectives involved data developed during this project. The Calculated objective was derived from measured data and eGRID emission factor information from the U.S. Environmental Protection Agency (USEPA) (USEPA, 2012). Note that each duplex has two housing units and that the performance measurements were taken for each individual housing unit.

Table 2. Performance objectives.

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Objectives					
DESIGN	1. Reduce modeled energy use of ZEH design compared to typically designed unit (*Energy*)	Modeled annual energy use per unit area	• Data on building components required to run energy models • Modeled energy use of ZEH unit design • Modeled energy use of typically designed unit[a]	ZEH model shows 50% less annual energy use (thousand Btu [kBtu] per square foot) than typically designed unit[b]	ZEH model showed 52% less energy use than typically designed unit
DESIGN	2. Reduce modeled energy use of ZEH design compared to national standards (*Energy*)	Modeled annual energy use per unit area	• Data on building components required to run energy models • Modeled energy use of ZEH unit design • Average annual energy use provided as national standard[c]	ZEH model shows 60% less annual energy use (kBtu per square foot) than the national average	ZEH model showed 72% less energy use than the national average
DESIGN	3. Modeled on-site energy generation is equal or greater than modeled energy use (*Energy*)	Modeled net energy use per year	• Data on building components required to run energy models • Modeled energy use of ZEH design • Modeled annual energy generation from PV panels and solar thermal	ZEH model shows energy generation (kBtu per year) is equal to or greater than design energy use[d]	ZEH model showed 8% more energy generation than design energy use
DESIGN	4. Reduce modeled potable water use of ZEH design compared to typically designed unit (*Water*)	Modeled annual water use per occupant	• Equipment specifications for building components required	ZEH design includes more efficient fixtures and fittings than typically designed unit[e]	Rated performance of ZEH toilets were 22% more efficient than the typically designed unit; lavatory faucets were 32% more efficient, and showers were 30% more efficient

Table 2. Performance objectives(continued).

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
MEASURED	5. Reduce measured energy use of ZEH compared to typically designed unit (*Energy*)	Measured annual energy use per unit area	• Metered whole building energy use of ZEH unit • Metered whole building energy use of typically designed unit • Average metered energy use of Fort Campbell unit complex[f]	ZEH shows 50% less energy use (kBtu per square foot) than a typically designed unit and Fort Campbell unit complex average	ZEH A: energy use was 29% less than average typically designed unit and 40% less than average Fort Campbell unit complex ZEH B: energy use was 19% less than average typically designed unit and 31% less than average Fort Campbell unit complex
	6. Reduce measured energy use of ZEH compared to national standard (*Energy*)	Measured annual energy use per unit area	• Metered whole building energy use of ZEH unit • Average annual energy use provided as national standard for homes[g]	ZEH shows 60% less energy use (kBtu per square foot) than national average	ZEH A: energy use was 63% less than national average ZEH B: energy use was 58% less than national average
	7. Annual measured on-site energy generation is equal to or greater than annual measured energy use (*Energy*)	Measured net energy use per year	• Metered whole building energy use of ZEH unit • Metered annual energy generation from PV panels and solar thermal	Annual ZEH energy generation (kBtu per year) is equal or greater than its energy use	ZEH A: energy generation was 79% of energy use ZEH B: energy generation was 67% of energy use
	8. Reduce measured heating, ventilation, and air conditioning [HVAC] system energy use compared to typically designed unit (*Energy*)	Metered HVAC system energy use per year	• Metered energy use of ZEH HVAC system • Metered energy use of typically designed unit HVAC system	ZEH HVAC system shows 60% less energy use (kBtu per year) than the HVAC system in the typically designed unit[h]	ZEH A: HVAC system energy use was 26% less than average typically designed unit ZEH B: HVAC system energy use was 33% less than average typically designed unit
	9. Reduce measured ZEH hot water energy use compared to typically designed unit (*Energy*)	Metered annual hot water use per occupant	• Metered energy use of ZEH hot water systems • Metered energy use of typically designed hot water systems • Number of typical occupants for each unit	ZEH hot water system shows 60% less energy use (kBtu per occupant per year) than hot water system of typically designed unit[i]	ZEH A: hot water system energy use was 39% less than average typically designed unit ZEH B: hot water system energy use was 3% less than average typically designed unit

Table 2. Performance objectives(continued).

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
MEASURED (continued)	10. Reduce measured ZEH lighting, plug load, and appliance energy use compared to typically designed unit (*Energy*)	Metered annual energy use associated with lighting, plug load, and appliances	• Metered energy use of ZEH lighting, plug load, and appliances • Metered energy use of typically designed lighting, plug load, and appliances • Number of typical occupants for each unit	ZEH shows 10% less annual energy use (kBtu per occupant) for lighting, 10% less annual energy use for plug loads, and 20% less energy use for appliances compared to typically designed unit[j]	ZEH A: lighting energy use was 33% less than average typically designed unit ZEH B: lighting energy use was 16% less than average typically designed unit ZEH A: plug load energy use was 4% less than average typically designed unit ZEH B: plug load energy use was 3% less than average typically designed unit ZEH A: appliance energy use was 32% less than average typically designed unit ZEH B: appliance energy use was 19% less than average typically designed unit
	11. Reduce measured ZEH potable water consumption compared to typically designed unit (*Water*)	Metered annual water use per occupant	• Metered whole building water use for ZEH • Metered whole building water use for typically designed unit • Number of typical occupants for each unit	ZEH shows 30% less water use (gallons per occupant) than typically designed unit[k]	ZEH A water use was 51% less than Baseline B. Sufficient data were not available to compare ZEH B water use.
CALCULATED	12. Reduce ZEH air emissions associated with measured electricity use (*Air Quality*)	Calculated emissions from energy generation sources using CO_2 equivalents as the indicator metric	• Metered whole building energy use for ZEH • Metered energy generation from PV panels • Metered whole building energy use for typically designed unit • Utility specific emissions data	ZEH related net emissions (CO_2 equivalents per year) are 100% lower than typically designed unit	ZEH A: emissions were 85% less than the average typically designed unit ZEH B: emissions were 75% less than the average typically designed unit

Table 2. Performance objectives(continued).

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
Qualitative Objectives					
MEASURED	13. ZEH maintenance is equal or less than typically designed unit maintenance *(Maintenance)*	Number of maintenance activities and time associated with these activities	• Number and hours of ZEH and typically designed unit preventative maintenance activities • Number and hours of ZEH and typically designed unit emergency maintenance activities	ZEH maintenance activities are equal or less than the typically designed unit maintenance activities[l]	ZEH preventative maintenance activities were more than the typically designed unit. ZEH emergency maintenance activities were approximately the same as the typically designed unit.
MEASURED	14. ZEH occupant satisfaction is equal to or higher than typically designed unit (*IEQ*)	Building occupant satisfaction feedback from occupant interviews	• Occupant satisfaction feedback from ZEH and typically designed unit regarding overall satisfaction with unit, and satisfaction with specific building features such as thermal comfort	ZEH shows equal or higher satisfaction as compared to the typically designed unit	ZEH satisfaction was equal to typically designed unit

[a] Modeled energy use for the typically designed duplex is 34.8 kBtu per square foot per the National Association of Home Builders Research Center (NAHB-RC). June 2008. Primary Energy and Sensitivity Analysis for Ft. Campbell J4B Model. Page 4.

[b] Basis for percent reduction success criteria: NAHB-RC. Zero Energy Homes. A Brief Primer. Page 13. http://www.toolbase.org/PDF/CaseStudies/ZEHPrimer.pdf

[c] National average for duplexes is 46.7 kBtu per square foot per the Residential Energy Consumption Survey. U.S. Energy Information Administration (EIA). 2001. RECS. Table CE1-5.2u. Total Energy Consumption and Expenditures by Square Feet and Household Demographics, 2001. http://www.eia.doe.gov/emeu/recs/recs2001/ce_pdf/enduse/ce1-52u_sqft_demo2001.pdf

[d] Basis for success criteria: NAHB-RC. Zero Energy Homes. A Brief Primer. Page 2. http://www.toolbase.org/PDF/CaseStudies/ZEHPrimer.pdf

[e] Basis for success criteria: U.S. Green Building Council (USGBC). Leadership in Energy and Environmental Design (LEED) for Homes 2008. High Efficiency and Very High Efficiency Fixtures and Fittings, Water Efficiency Credits 3.1 and 3.2. http://www.usgbc.org/ShowFile.aspx?DocumentID=3638

[f] Average measured energy use for Ft. Campbell duplexes has been 48.1 kBtu per square foot per the NAHB-RC. November 4, 2008. NAHB-RC. Energy Use comparison of simulation energy use data compared with measured data from 6-J4B units.

[g] National average for duplexes is 46.7 kBtu per square foot per the RECS. EIA. 2001. RECS. Table CE1-5.2u. Total Energy Consumption and Expenditures by Square Feet and Household Demographics, 2001. http://www.eia.doe.gov/emeu/recs/recs2001/ce_pdf/enduse/ce1-52u_sqft_demo2001.pdf

[h] Basis for success criteria: NAHB-RC. June 2008. Preliminary Energy and Sensitivity Analysis for Ft. Campbell J4B Model. Table 2 (Base Design 7537 kWh) and EnergyGauge simulation 10/15/2008. (Option 2 ZEH 2566 kilowatt-hour [kWh])

[I] Basis for success criteria: NAHB-RC. June 2008. Preliminary Energy and Sensitivity Analysis for Ft. Campbell J4B Model. Table 2 (Base Design 3774 kWh) and EnergyGauge simulation 10/15/2008. (Option 2 ZEH 473 kWh)

[j] Basis for success criteria: NAHB-RC. June 2008. Preliminary Energy and Sensitivity Analysis for Ft. Campbell J4B Model. Table 2 (Base Design 2712 kWh) and EnergyGauge simulation 10/15/2008. (Option 2 ZEH 2204 kWh)

[k] Basis for success criteria: USGBC. LEED for Homes 2008. High Efficiency and Very High Efficiency Fixtures and Fittings, Water Efficiency Credits 3.1 and 3.2. http://www.usgbc.org/ShowFile.aspx?DocumentID=3638

[l] Note: There is a perception that high performance buildings have increased maintenance over typically designed buildings. Thus, this metric is being used to compare levels of maintenance.

4.0 SITE DESCRIPTION

Fort Campbell was the host installation for this project. Fort Campbell, home of the 101st Airborne Division, has a population of approximately 30,000 soldiers, with an on-post residency of about 25,000 (including family members). Family housing at Fort Campbell has been privatized, and Lend Lease (formerly Actus Lend Lease) is the property manager for Fort Campbell. The Woodlands neighborhood development is managed by Campbell Crossing LLC, which is operated by Lend Lease.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The housing units used in this study are located in the Woodlands subdivision of Fort Campbell. The Woodlands is composed of 236 duplex buildings (each duplex includes two single family housing units) and 51 single family housing units, for a total of 523 individual units. Fort Campbell is located on the border of Kentucky and Tennessee in the hot-humid climate zone.[1] The Woodlands is adjacent to the installation, located southeast of post. In total, the subdivision includes 470 new Junior Non-Commissioned Officer (JNCO) and Senior Non-Commissioned Officer (SNCO) housing units that were constructed by October 2011. Figure 3 shows the Woodlands neighborhood site plan.

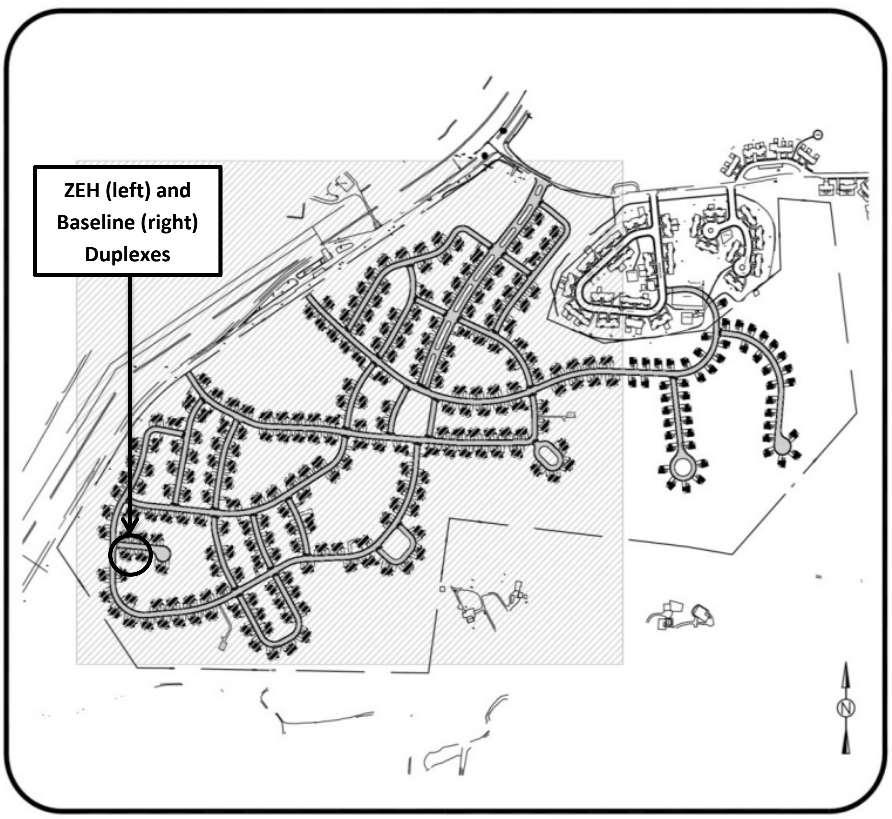

Figure 3. Woodlands site plan (Luckett & Farley).

[1] Climate zones are defined in the RECS, available at http://www.eia.gov/consumption/residential/maps.cfm.

The average cost of electricity in 2011 was 7.9¢/ kilowatt-hour (kWh). The average cost of water was $1.433 per thousand gallons from January through September 2011, and $1.58 per thousand gallons from October through December 2011. The occupants did not pay any energy or water bills during the study period; utility costs for the housing units were covered by Campbell Crossing.

Fort Campbell has an average yearly solar potential for a flat collector tilted at 37°of 4.8 kWh/square meters (m^2)/day (National Aeronautics and Space Administration [NASA], 2010).

4.2 FACILITY/SITE CONDITIONS

ZEH designs may be most successful and cost-effective in areas with high energy costs, good renewable energy resource potential, and where the home designs are more adaptable. Whole building performance measurement can be performed in any location. Energy and water use data, and building characteristics are necessary for performance measurement.

4.2.1 Geographic Criteria

Some sort of renewable energy system is needed to generate the energy required for a net zero house. In many locations, PV systems are the most practical from an available space perspective, but may not be a cost-effective technology to meet this requirement. PV systems tend to be most cost effective in areas with high solar resource potential and high energy costs. Ground-source heat pumps (GSHP) are more effective in locations where there are both high winter heating and high summer cooling loads. In addition, suitable soil conditions are a factor that affects GSHP performance.

4.2.2 Facility Criteria

This project used small scale renewable systems to achieve net zero design because the buildings were small scale, and only one duplex was analyzed. If net zero energy on a community or site level was desired, a larger scale renewable energy project (e.g., ground mounted PV or geothermal-generated energy) could be more cost effective depending on the site characteristics.

ZEHs that implement more comprehensive integrated design than was possible on this project (maintaining housing equity was a project goal), can result in buildings optimized for energy efficiency and comfort. Like many energy efficient technologies, ZEHs are typically most cost effective in locations with high utility rates, and where state, utility, and/or municipality incentives are available for renewable energy or energy efficiency projects.

5.0 TEST DESIGN

The ESTCP project team contributed to the ZEH design by providing energy modeling input and technical assistance on specific technologies, facilitating the design charrette, identifying and purchasing monitoring equipment, developing performance criteria, and selecting and training occupants of the ZEH.

5.1 CONCEPTUAL TEST DESIGN

The ESTCP team facilitated installation and calibration of energy and water monitoring equipment at the ZEH units and the typically designed units during construction. After the homes were constructed, a Home Rater tested building HVAC and envelope systems prior to occupation. This testing process is a type of commissioning for residential buildings and included blower door tests, HVAC performance validation, and building envelope performance rating confirmation. Performance data was collected, verified, and analyzed for all four housing units from October 2011 through February 2012 (calendar year 2011 was used as the primary analysis period).

5.2 BASELINE CHARACTERIZATION

The baseline comparisons include energy modeling, national standards for the design, measured performance of the typically designed units, and average measured performance of similar Woodlands residences.

Engaging occupants to conserve energy is a vital component of achieving net zero energy in a ZEH. Occupants open to being part of the project and receiving feedback on their energy use was a pre-requisite for selection. Selecting occupants with extremely high or low historical energy use prior to moving into the new homes may have misrepresented the impact of receiving regular feedback regarding their energy use while living in the new homes. Therefore, occupants with historical average energy use were selected. To control for variance caused by occupant behavior to the extent possible, families similar in size, typical daily occupancy, and electronic equipment were sought as occupants for the housing units. Families were invited to apply to be part of the study, and interviews were conducted to determine suitability. The characteristics of the families selected are listed in Table 3.

Table 3. Occupant family characteristics.

Characteristic	Baseline A	Baseline B	ZEH A (first family)	ZEH A (second family)	ZEH B
Number of adults[a]	2	2	2	2	2
Number of children	2	2	2	2	2
Hours home during the day	2-4	0-3	3-6	Not Recorded	3-6
Electronics	Televisions: 3 Computers: 2	Televisions: 4 Computers: 2	Televisions: 4 Computers: 2 Freezer	Televisions: 4 Computers: 1 Laptops: 2 Freezer Alarm system	Televisions: 4 Computers: 2

[a] Varied during the course of the study due to deployed spouses.

5.3 DESIGN AND LAYOUT OF ZEH TECHNOLOGY COMPONENTS

The starting point for designing the ZEH was the existing typical designed duplexes that Campbell Crossing currently builds. This two-story duplex provides homes for two families. Each family has four bedrooms and 2007 square feet of living space with 2.5 bathrooms on a slab foundation (no basements). The ZEH duplex and baseline floor plans are identical other than the solar hot water tank being placed in the powder room closet in the ZEHs, while the hot water tanks were placed in the mechanical rooms in the baseline units. The design features of the constructed ZEH and baseline housing units are pictured in Figure 4.

Baseline Design	ZEH Design
Air Source Heat Pump (8.45 HSPF, 13 SEER)	Ground Source Heat Pump 4.0 COP, 18 SEER)
Electric Water Heater	Solar Water Heater
2x4 Metal Stud Exterior Walls	2x6 Wood Stud Exterior Walls
R-15 Wall Insulation R-49 Ceiling Insulation R-0.5 Sheathing	R-19.8 Wall Insulation R-60 Ceiling Insulation R-5 Sheathing
Occupant-provided Clothes Washer and Dryer	Project-provided High Efficiency Clothes Washer and Dryer
No Envelope Sealant	Envelope Perimeter Sealant

Figure 4. Design features of baseline and ZEH housing units.

In October 2010, prior to moving into the housing units, the ZEH and baseline families participated in a 1-day occupant training program. The training included an overview of the goals and objectives of the ZEH project, the families' influence on the success of the project, and proper equipment usage. The training also provided a synopsis of the real-time metering equipment so that the families understood how to monitor and control their electricity usage. The primary real-time metering device was an in-home energy monitor, called The Energy Detective (TED) (Figure 5). This device showed both real time whole-house energy use and tracked cumulative energy use per day and per month, as well as the highest and lowest power load recorded during a given day.

Figure 5. The Energy Detective (TED).

ShowerMinders were also installed in all showers (Figure 6). These devices informed the users how long the shower was turned on; a green light turned on during the first 5 minutes; from 5 minutes to 8 minutes the light turned yellow, and after 8 minutes the light turned red. The device did not directly affect the water flow.

Figure 6. ShowerMinder.

Monthly written feedback on energy and water use was provided to the occupants, and discussed with them over the phone. The purpose of this interaction was to help both the occupants and the ESTCP team understand the underlying factors for specific consumption patterns.

A final survey was distributed after the monitoring period concluded to understand what elements of the study were most helpful and influential in changing occupant behavior. All of the families noted that the TED was one of the most effective elements that influenced their behavior. Many families also indicated that the other real-time feedback device, the ShowerMinder, was an effective tool. The monthly energy reports and call with the ESTCP team was also noted as an element that affected energy use.

5.4 OPERATIONAL TESTING

Operational testing consisted of three phases: (1) home energy rating prior to occupancy; (2) monitoring system installation and calibration; and (3) data collection, normalization, and comparisons after the families moved into the housing units (Table 4).

Table 4. Operational testing phases and dates.

Phase	Dates
Home Energy Rating	October 2010
Monitoring system installation and calibration	September-October 2010
Families move into the housing units	October 2010
Data collection, normalization, and comparisons	October-December 2011

Home Energy Rating Prior to Occupancy

Campbell Crossing hired Home Energy Concepts Corporation to conduct a home energy rating, required for LEED certification. This was completed after construction, but prior to occupation. As part of this process, the mechanical system and building shell features were tested and performance was verified. In addition, a blower door test was conducted on each of the ZEHs to determine infiltration rates. ZEH A had an infiltration rate of 1168 cubic feet per minute (CFM) at a pressure difference of 50 Pascals (CFM50) and the ZEH B had a rate of 1157 CFM50. Based on design, the infiltration rate was expected to be half of this value, specifically 595 CFM50.

Duct leakage to the outside was 44 CFM for ZEH A and 48 for ZEH B. These rates are close to design intent (40 CFM). The test report also noted that the energy recovery ventilation system was balanced and operating at 80 CFM. Based on design, it was estimated that a ventilation rate of 60 CFM was needed. The actual system therefore introduced one third more air than is needed. This would theoretically increase the energy use of the HVAC system, but it is within typical operating parameters and has a relatively small impact on energy use in comparison to other variances such as infiltration.

Based on these test results, it appeared that the building envelope was not as tight as designed. This is likely, in part, due to the design changes, but it is also possible that proper sealing was not completely achieved during construction. Campbell Crossing had initially intended to hire a company to oversee construction, but did not do so, which may have affected the quality of the construction. The housing units still achieved a low Home Energy Rating System (HERS) index of -5, meaning they were rated to generate more energy than they would consume (a rating of 0 indicates no net energy is consumed; a rating of 100 indicates a standard new home).

Monitoring System Installation and Calibration of ZEH and Typically Designed Units

All monitoring equipment was installed in September 2010, after construction but prior to occupancy. A branch circuit power meter installed at the energy panel gathered interval electricity data on the building systems. Measurements of temperature, relative humidity, and water consumption were metered individually and fed to the data acquisition system; over 170 different monitoring points were installed across the four homes. In October 2010, the ESTCP team tested the monitoring equipment to check that all meters were tracking energy consumption at expected levels and patterns. During the monitoring period, data were routinely uploaded by the ESTCP team and checked for consistency.

Data Collection, Normalization, and Comparison

The families moved into the housing units in October 2010. The period used for data normalization and comparison was January through December 2011. Data from October through December 2010 were not included in the monitoring period because of data loss in ZEH B from equipment failure that was likely caused by lightning storms. This equipment failure event required coordination with subcontractors to send and install new equipment, and Fort Campbell personnel to schedule time with the family to access the unit and reinstall the equipment.

In June 2011, the monitoring system failed again in ZEH B and Baseline A, once more likely due to severe weather. New equipment was again installed, although not all water flow meters and indoor temperature sensors regained functionality.

In addition to the data collection equipment installed in the housing units, the housing units were metered by the utility company that provides electricity to all housing units in the Woodlands neighborhood. This metered monthly whole-house energy consumption provided additional data points for the ESTCP team for analysis and comparison.

The collected data were used to develop monthly energy reports that were shared with the families. The first page of the report (Figure 7) included daily energy consumption. Each day was color coded to indicate the level of energy consumption. The color coding was based on the expected monthly consumption according to modeled data: green indicated days where energy consumption was below the target; yellow indicated days where energy consumption exceeded the target by up to 25%; and red indicated days where energy consumption exceeded the target by more than 25%. On red days, the two end uses with higher than typical energy consumption were highlighted with an icon so the family could recognize what may have contributed to the higher energy consumption. For example, Figure 7 shows that on Thanksgiving (November 24) the highest end uses were plug loads and kitchen appliances. Displaying the daily consumption in the form of a calendar allowed the families to more easily compare their energy consumption with their schedule and identify events that may have influenced their energy use (e.g., vacations, visitors, severe weather).

The second page of the report (Figure 8) provided more detailed energy consumption by end use so the families could see how individual end uses affected their energy consumption. The four lowest energy consumption days were highlighted in green and the four highest consumption days were highlighted in red. The monthly energy comparison allowed each family to see how their consumption compared to the other housing units in the study, and the other housing units in the neighborhood (“Average Woodlands”). Daily solar output data were provided to the ZEH families. Energy tips changed monthly and served as reminders on ways to reduce energy use.

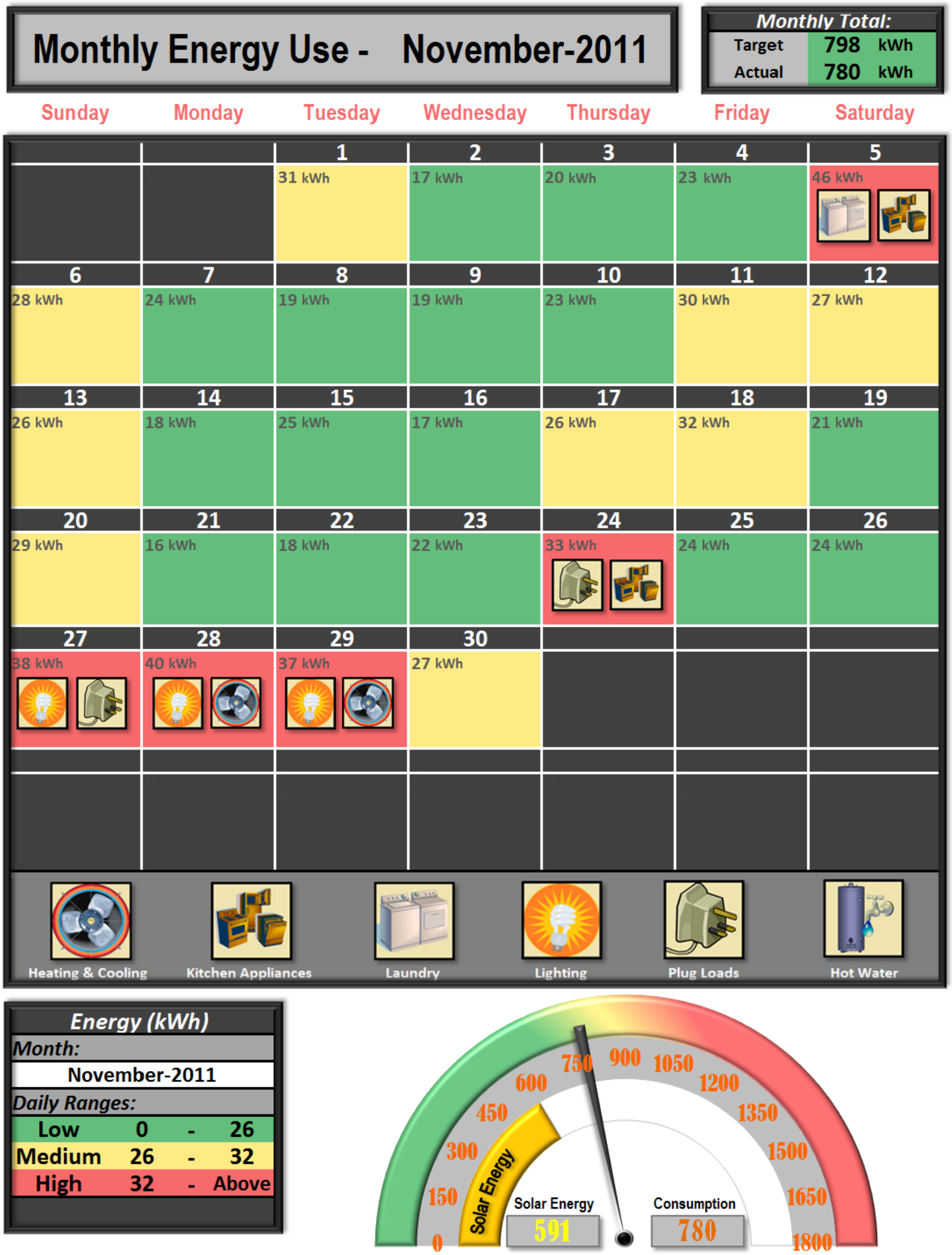

Figure 7. Monthly energy report example (Part 1)**.**

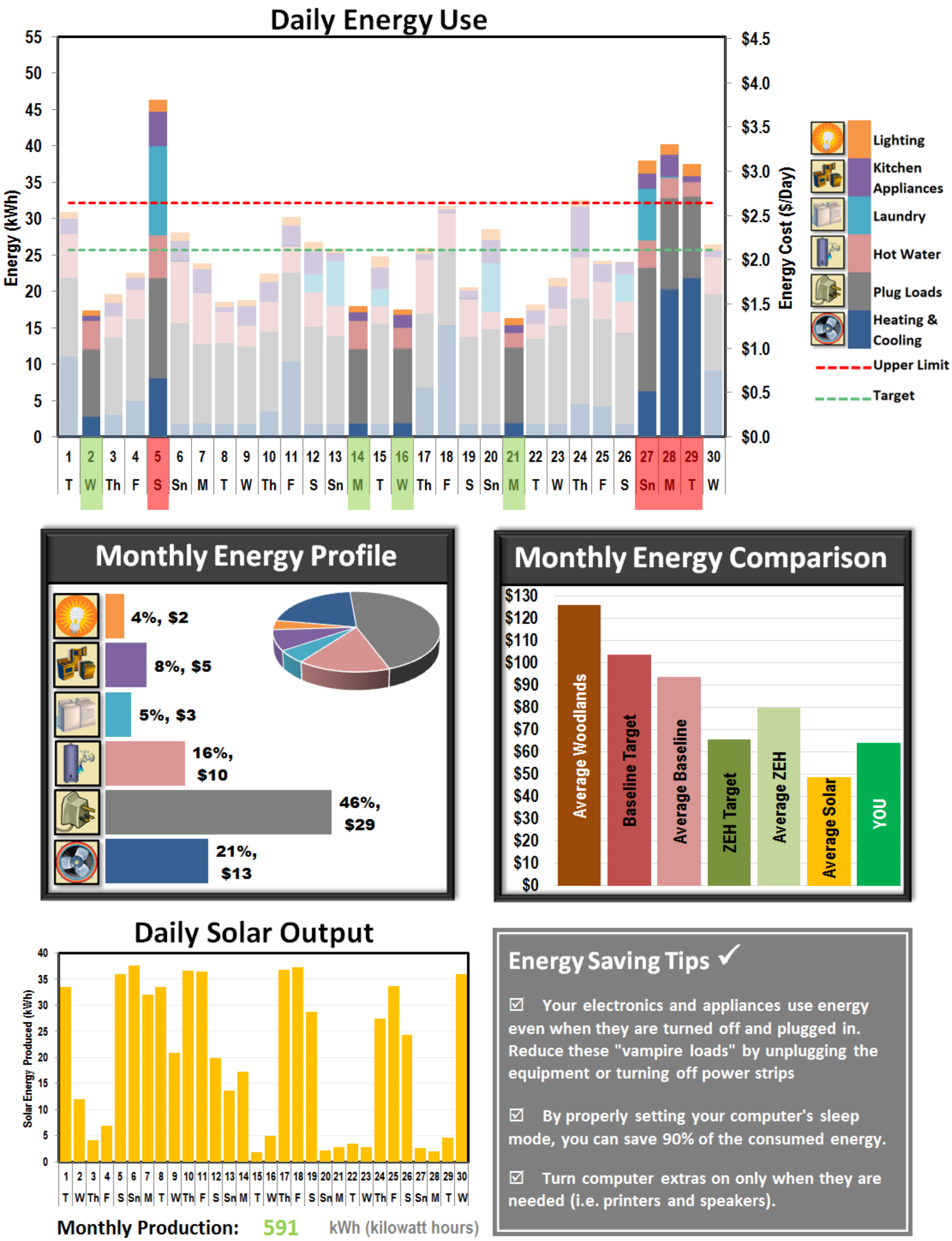

Figure 8. Monthly energy report example (Part 2)**.**

After the monitoring period concluded, the monitoring system was left in the homes in case Campbell Crossing wished to continue providing more detailed energy reports to the occupants. The ESTCP team worked with Lend Lease to transfer knowledge on collecting, analyzing, and communicating the detailed monitoring data. The goal was for the Lend Lease team to continue delivering more detailed energy data to the occupants. A methodology had been established for transferring data from the online database where it is stored to a workable spreadsheet. Training was provided regarding the data analysis and communication strategies used. Time and resource constraints have limited the Lend Lease team's ability to continue to provide the detailed monthly analysis.

5.5 SAMPLING PROTOCOL

The data collected from the housing units included 5-minute intervals for a 12-month period for over 150 separate monitoring points. Additionally monthly energy data was collected from the local utility, Minol. Fort Campbell uses Minol data for official records and provides these data to residents across the installation, so Minol data were used for the annual and monthly total energy use comparisons in this report. The energy data collected by the ESTCP meters were used for more detailed comparisons of smaller time scales and submetered energy uses.

5.6 SAMPLING RESULTS

A summary of the monitored monthly energy data for each baseline and ZEH unit are shown in Table 5 through Table 8. Table 9 includes the monthly Minol data recorded that was provided to the ESTCP team. Differences between the submetered end use data and the Minol data were due to meter calibration, accuracy, and missing data.

Table 5. Baseline A sub-metered data (kWh)**.**

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11[a]	Aug-11[a]	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	206	227	304	299	362	290	NR	NR	311	328	333	491
Lighting	53	71	56	72	101	62	NR	NR	95	109	101	128
Dishwasher	0	0	0	0	1	0	NR	NR	0	0	0	0
Dryer	82	97	94	65	138	65	NR	NR	81	106	107	154
Clothes Washer	5	6	7	5	10	5	NR	NR	7	9	7	11
HVAC	2138	950	501	210	289	400	NR	NR	140	186	310	569
Range	21	15	17	20	41	9	NR	NR	24	20	28	59
Refrigerator	28	28	32	32	42	31	NR	NR	38	35	34	41
Water Heater	246	194	171	168	231	122	NR	NR	153	174	218	358

[a] NR indicates no recorded data due to meter malfunction.

Table 6. Baseline B sub-metered data (kWh)**.**

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	330	256	278	233	319	329	375	383	221	316	342	167
Lighting	102	99	79	85	95	89	92	101	67	105	104	96
Dishwasher	5	9	9	6	5	4	5	3	2	2	7	2
Dryer	102	106	136	103	178	101	83	162	101	122	124	96
Clothes Washer	2	2	3	1	3	2	1	4	2	3	3	2
HVAC	1248	767	603	211	194	516	689	669	275	162	225	632
Range	26	31	30	13	26	17	13	28	25	26	43	12
Refrigerator	37	31	36	37	37	34	31	39	32	37	39	27
Water Heater	341	331	463	256	332	215	177	359	296	380	439	330

Table 1. ZEH A sub-metered data (kWh)**.**

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	293	267	359	328	300	322	342	359	349	243	419	447
Lighting	59	53	73	68	53	66	71	68	95	29	30	31
Dishwasher	11	9	15	12	9	12	10	15	16	5	15	15
Dryer	56	40	68	55	53	62	56	60	78	25	39	38
Clothes Washer	6	5	8	5	5	6	5	6	8	2	2	2
HVAC	736	526	312	124	97	344	604	468	182	87	113	389
Range	10	5	16	13	14	16	12	18	18	10	25	29
Refrigerator	33	27	32	32	30	32	32	34	37	25	25	24
Water Heater	169	142	208	164	138	127	113	128	141	86	113	128

Table 8. ZEH B sub-metered data (kWh)**.**

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11[a]	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	274	283	282	327	329	346	NR	321	327	325	348	402
Lighting	75	72	61	80	72	88	NR	89	109	69	92	105
Dishwasher	8	12	12	14	11	11	NR	9	14	11	14	17
Dryer	54	93	68	86	89	93	NR	85	93	79	95	93
Clothes Washer	3	6	5	6	6	6	NR	6	7	5	6	6
HVAC	566	457	261	110	176	330	NR	269	135	173	250	518
Range	16	21	14	18	15	15	NR	7	10	17	23	29
Refrigerator	31	32	33	39	43	46	NR	41	39	33	41	39
Water Heater	202	374	263	296	296	250	NR	181	235	234	296	354

[a] NR indicates no recorded data due to meter malfunction.

Table 9. Minol data (kWh).

Home	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Baseline A	2603	1580	1179	899	1172	1042	1533	1248	926	1015	1168	1857
Baseline B	2747	1975	2007	1034	1282	1356	1583	1834	1054	1234	1421	1485
ZEH A	1447	1167	1162	859	785	995	1260	1246	1002	579	850	1129
ZEH B	1493	1414	996	1010	1078	1129	1285	1056	995	989	1196	1565

6.0 PERFORMANCE ASSESSMENT

The performance objectives aligned with the goals of performance measurement: to evaluate the design, energy use, water use, maintenance needs, and occupant satisfaction of the ZEHs. Modeled energy consumption informed the design performance objectives, while measured whole home and submetered energy use were used to evaluate the measured objectives. Water use was also tracked, as were maintenance records and costs. Energy and water use was translated into energy and water costs using Fort Campbell's average utility rates. GHG reduction was calculated using the measured energy savings and regional emission factors for the Fort Campbell area.

Performance objectives listed in Section 3 are described in this section with a short discussion of the results. Additional information on the development, measurement, and analysis of each objective are provided in the Final ESTCP Report.

6.1 ENERGY PERFORMANCE RESULTS

Energy use is the most frequently tracked metric for high performance and sustainably designed buildings. Reducing energy consumption has a major effect on a building's environmental footprint, including carbon-related impacts. Because this project had the ultimate goal of achieving net zero energy consumption, the majority of the objectives, Performance Objectives 1-3 and 5-10, focused on energy systems.

Design related performance objectives, Objectives 1-3, compared modeled energy use based on the ZEH and baseline unit design. All three energy-related design objectives were met. Measured performance objectives, Objectives 5-10, compared measured energy of the homes.

Objective 5 compared the whole home energy use of the ZEH with the baseline unit. This performance objective, reducing energy use by 50% from the baseline unit, was not met. ZEH A used 29% less energy than the average baseline unit, and ZEH B used 19% less energy. However, the baseline units also performed better than expected using 15% less energy than similar homes in the Woodlands community. This difference between the average baseline home energy use and the average Woodlands home was notable, indicating that providing detailed energy use information (especially with the real-time energy devices such as TED) likely influenced the families' energy use patterns.

The Woodlands housing units also consumed less energy than originally expected. Data from 2008 provided by Lend Lease indicated that similar housing units at Fort Campbell consumed an average 27,327 kWh per unit, or 46.5 kBtu per square foot, which is in line with 2001 RECs data. In comparison, the average Woodlands consumption in 2011 was 20,722 kWh per unit, or 28.4 kBtu per square foot, which is 20% less than 2009 RECs data for the south census region homes constructed after 2000. While many factors may have influenced this change in energy consumption, the trend could be consistent with more efficient lighting and appliances in Lend Lease's standard home design and increased awareness of energy efficiency goals.

Objectives 8 and 9 provide details on how the HVAC energy use and occupant behavior had a significant impact on the ZEHs ability to achieve Objective 5. In brief, the reasons include the lack of temperature setbacks, higher than expected infiltration rates, differences in expected interior temperature setpoints, and variances in occupant laundry practices.

Objective 6, reduce measured energy use of the ZEH by 60% compared to national standards (RECS), was met. Figure 9 and Table 10 summarize the performance comparison between the units and the baselines.

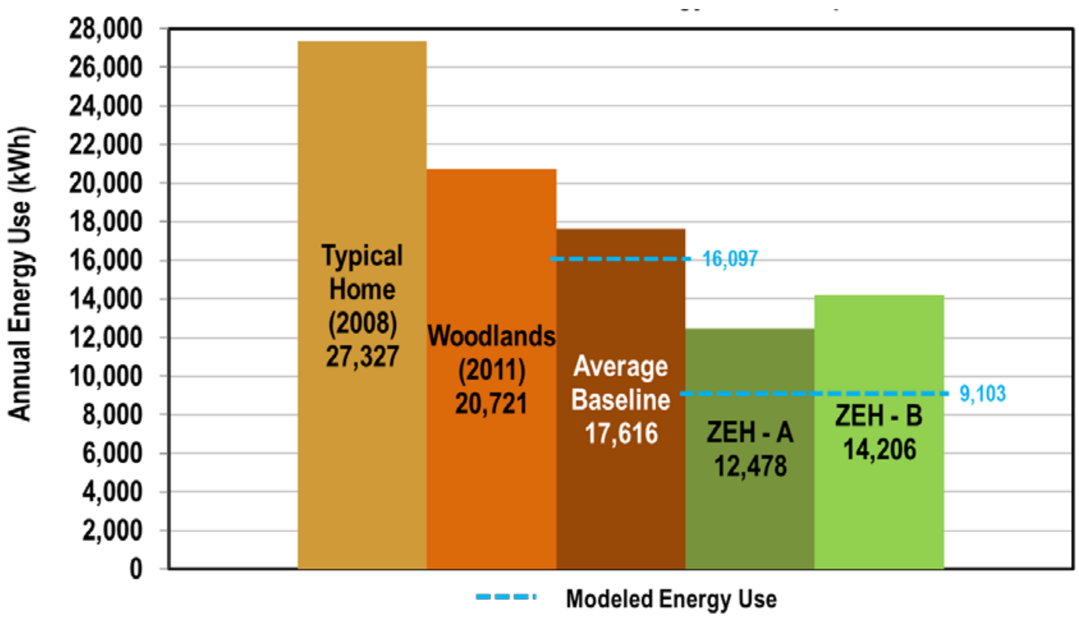

Figure 9. Annual energy use comparison.

Table 10. ZEH energy performance summary.

Unit	Baseline	Woodlands (2011)	Typical Fort Campbell (2008)	RECS (2001)
ZEH A	-29%	-40%	-54%	-77%
ZEH B	-19%	-31%	-48%	-58%

Objective 7, annual measured on-site energy generation is equal to or greater than measured annual energy use, was not met as both ZEHs used more energy than the amount of solar energy generated (Figure 10). The ZEH units did not achieve net zero energy in 2011 because the units used more energy than expected, and less energy was generated by the PV panels than expected. Consistent with the typical ZEH approach, the solar panels were sized to produce as much energy as the housing units were modeled to consume. Many assumptions were required to create this modeled energy consumption and generation, including technology performance, frequency of use, and environmental characteristics. Successfully reaching net zero energy depends on how closely the assumptions matched the actual use patterns. The more detailed submetered data captured in Objectives 8-10 provides insight into why the units did not achieve net zero energy in 2011.

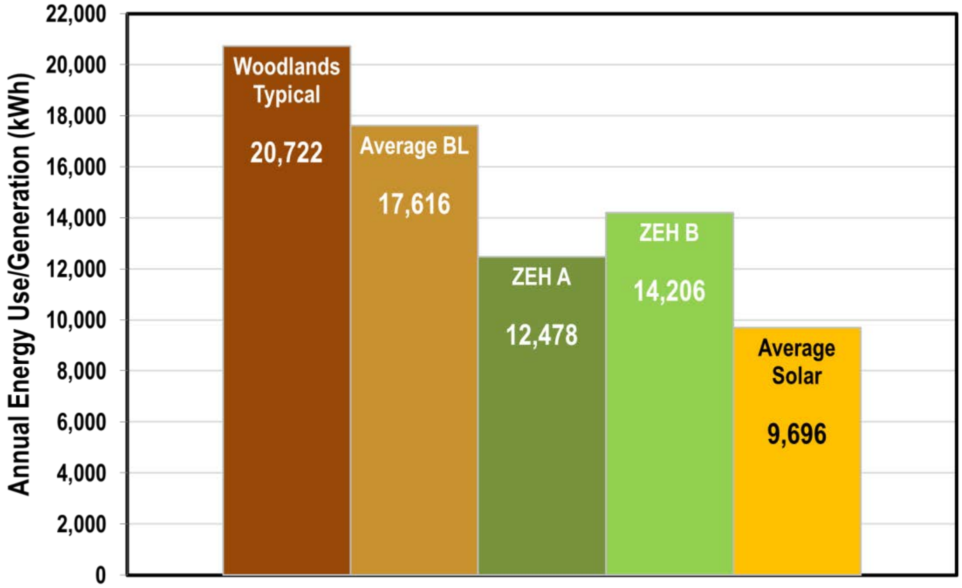

Figure 10. Annual total energy use.

Objective 8, reduce measured HVAC system energy use by 60% compared to typically designed unit, was not met. ZEH A's HVAC system showed 26% less energy consumption than the average typically designed unit, while ZEH B showed 33% less energy consumption. The ZEH housing units consumed 40% more HVAC energy than the model predicted (Figure 11).

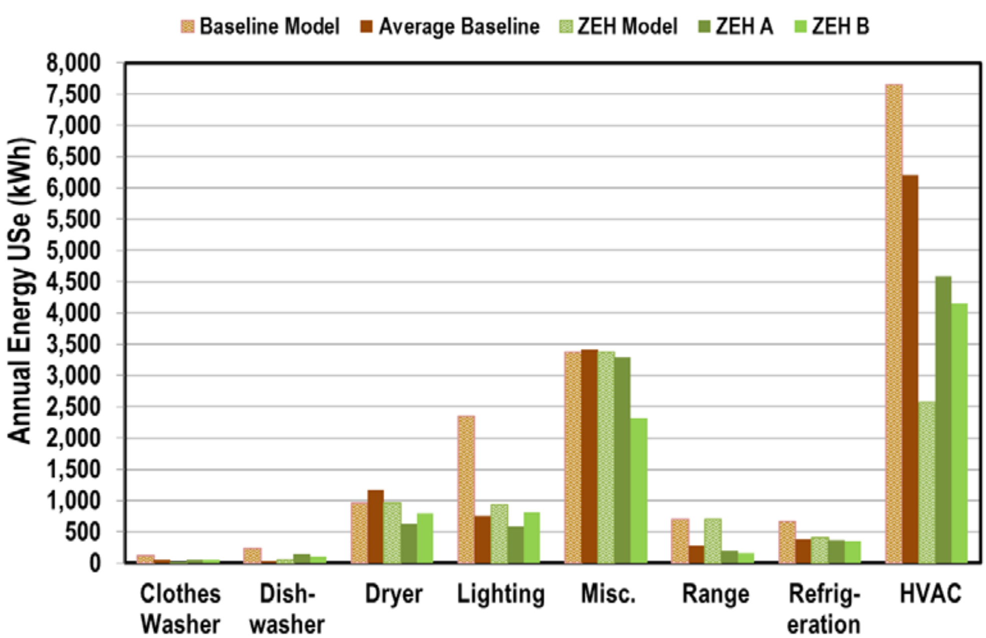

Figure 11. Modeled and actual end use comparison.

The interior temperature setpoints in both the ZEHs and the baseline housing units tended to be higher than expected during the heating season and lower than expected during the cooling season. In addition, the ZEH interior temperatures tended to stay constant during the daytime heating season, while in the baseline housing units the temperature went down by a few degrees. This difference indicated occupancy variances (the occupants in the baseline housing units tended to be gone more often during the day than the ZEH occupants) and/or programmed temperature setbacks in the baseline housing units and not in the ZEHs. Another factor affecting HVAC energy consumption was infiltration rates that during the home energy rating measured twice as high as the model predicted. Modeling estimates indicated that differences between modeled and actual interior temperature setpoints resulted in 30% more HVAC consumption than expected, and higher infiltration rates resulted in 20% higher consumption.

Objective 9, reduce measured ZEH hot water system energy use by 60% compared to typically designed unit, was not met. ZEH A consumed 39% less hot water energy compared with the average typically designed unit, while ZEH B consumed 3% less hot water energy. Different laundry habits and variances in occupancy contributed to not meeting the objective.

The solar hot water comparison showed that on average, Baseline B used 131 watts per gallon of hot water delivered, while ZEH A used 112 watts per gallon of hot water delivered, a difference of 14%. Figure 12 shows the monthly power per gallon comparison.

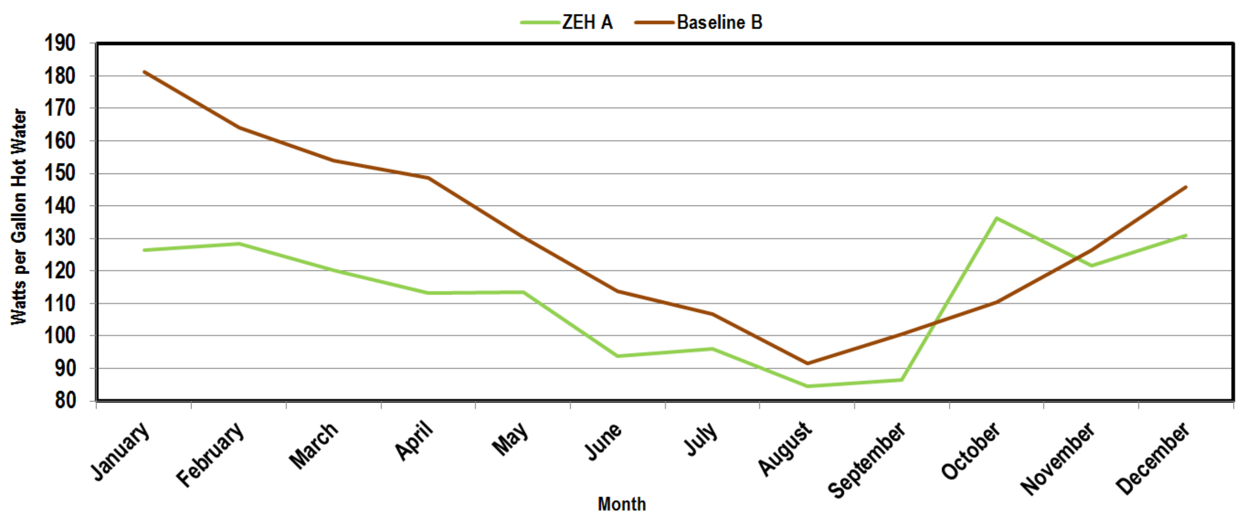

Figure 12. Monthly hot water comparison.

ZEH A consistently used less power per gallon of hot water consumed than Baseline B (except in October when usage decreased because the ZEH family moved so the home was empty for half of the month), indicating the contribution of the solar hot water heater. However, Baseline B also used more water on average than ZEH A (Figure 13). It is unclear if the solar hot water system or the lower volume of hot water used compared to Baseline B contributed more to the lower energy use per gallon of hot water consumed in ZEH A.

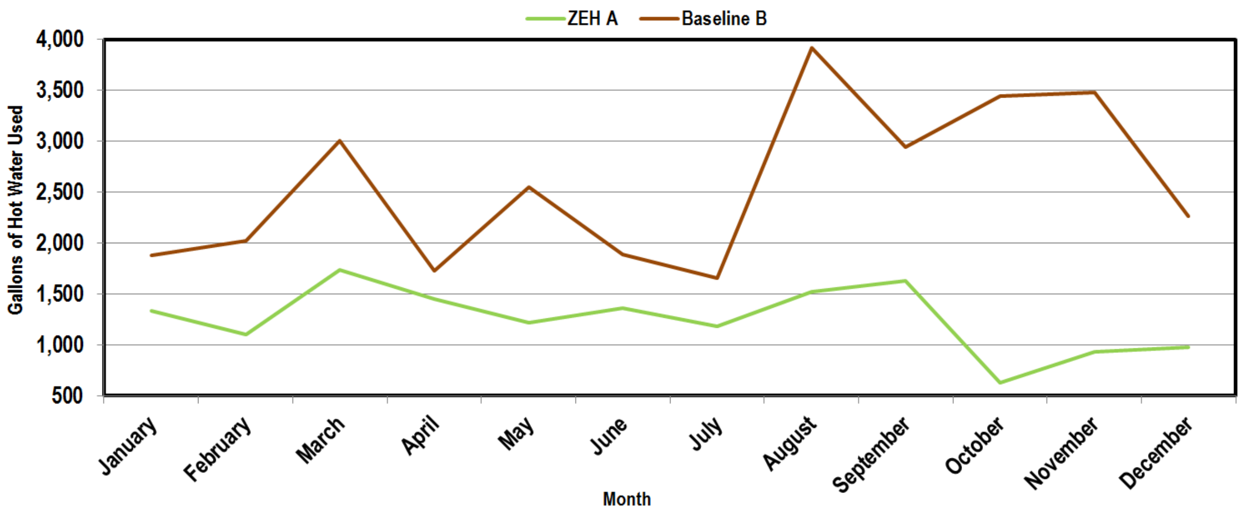

Figure 13. Monthly hot water consumption.

While the data indicate that the solar hot water system reduced hot water electricity use in ZEH A compared to Baseline B without sufficient metering in place, conclusions cannot be made about the amount of total hot water energy use provided by the solar hot water system.

Objective 10, reduce measured ZEH lighting (10% reduction), plug load (10% reduction), and appliance energy use (20% reduction) compared to typically designed unit, was met for all end uses. The ZEHs showed 33% and 16% less energy use per occupant for lighting, 10% and 26% less energy use for plug loads, 32% and 19% less energy use for appliances.

6.2 WATER PERFORMANCE RESULTS

Objective 4, reduce modeled potable water demand of ZEH design compared to typically designed unit by using more efficient fixtures and fittings, was met. ZEH design fixtures and fittings were 22 to 32% more efficient than the typically designed fixtures and fittings.

Objective 11, reduce measured potable water use by 30% compared to typically designed unit, was met. ZEH A consumed 51% less water per person than Baseline B in 2011.[2] The ZEH A family was gone more weeks during the year than the Baseline A family, and had more weeks with visitors.[3] Accounting for vacation and visitors, ZEH A consumed 48% less water per person than Baseline B. ZEH A consumed 41% less gallons per square foot than Baseline B.

6.3 AIR QUALITY PERFORMANCE RESULTS

Objective 12, reduce ZEH air emissions associated with measured electricity use by 100%, was not met. Because the ZEH and baseline housing units use electricity for all energy needs, the percent difference in GHG emissions between the two housing units was similar to the difference in energy consumption. ZEH A net emissions in 2011 were 1617 kilograms carbon dioxide

[2] Water flow data were not available from June through December for Baseline A and ZEH B; therefore, data from Baseline B and ZEH A formed the basis for the water consumption analysis.
[3] Conservatively assumed one more person in the home during the periods with visitors.

equivalents (CO_2e), and ZEH B net emissions were 2894 kilograms CO_2e, or 85% and 73% lower than the average baseline home, respectively.

6.4 MAINTENANCE PERFORMANCE RESULTS

Objective 13, ZEH maintenance is equal to or less than typically designed unit maintenance, involved compiling the number of preventative and emergency maintenance activities of each ZEH unit and comparing them to the typically designed units.

Objective 13 was not met. ZEH emergency maintenance activities were about the same as they were for typically designed units, but the ZEH-specific technologies resulted in more preventative maintenance activities than the typically designed units. Cleaning and replacing the energy recovery ventilation system filters was the primary preventative maintenance activity in the ZEHs that was not performed in the typically designed units.

Table 11 indicates the number and hours of preventative and emergency maintenance calls in 2011 for each home.

Table 11. 2011 maintenance activity summary.

Activity	Baseline A	Baseline B	ZEH A	ZEH B
Preventative				
Number of calls	0	0	2	2
Total annual hours	0	0	1.75	1.75
Emergency				
Number of calls	2	2	2	1
Total annual hours	1	1.5	2	0.7

6.5 OCCUPANT SATISFACTION PERFORMANCE RESULTS

Objective 14, ZEH occupant satisfaction is equal to or higher than typically designed unit, involved interviews with the building occupants of the ZEH units and the typically designed units. Occupant satisfaction was qualitatively evaluated based on monthly interviews with the occupants and a final set of questions after the monitoring period was completed. The questions covered overall building satisfaction and thermal comfort.

The occupant satisfaction metrics were also analyzed in relation to other performance metrics, for example, thermal comfort and energy performance. Monthly interviews and the results from the final set of questions indicated that there was no notable difference in satisfaction between the occupants of the ZEHs and typically designed units.

7.0 COST ASSESSMENT

The Whole Building Design Guide published by the National Institute of Building Sciences and National Institute of Standards and Technology's (NIST) Life-Cycle Costing Manual for the Federal Energy Management Program Handbook 135 (NIST, 1996) was used for the LCC analysis. The Building Life-Cycle Cost Program (BLCC) 5 5.3-08, developed by NIST, was evaluated to determine appropriateness for use on this project. The BLCC5 software was not used because it was determined it may not be able to handle the public-private venture (PPV) funding that Campbell Crossing used for the ZEH.

Using these guidance documents, critical cost items and data collection requirements were identified during the design. Working with Campbell Crossing, a data collection process was drafted and communicated to the appropriate construction personnel. Only differential costs between the baseline housing units and ZEHs were included in the analysis, as these were the only costs made available for proprietary reasons.

Investment-related costs include those associated with the financial investment of the project. Land acquisition and community infrastructure costs were treated as sunk costs for this analysis and excluded. If ZEHs were constructed on a large scale, additional infrastructure costs related to optimal house orientation (to take advantage of solar benefits) may be incurred. Building replacement will not be required within the analysis periods (25 and 40 years); therefore, no building replacement costs were included. Because Campbell Crossing's physical assets revert back to the military at the end of their 50-year contract, residual costs are not included.

7.1 COST DRIVERS

Primary cost drivers for this project were the renewable energy systems, the ground source heat pump, and the energy recovery ventilator.

The PV system used to generate energy for the ZEHs was the most critical cost driver, accounting for almost 50% of the cost differential of the ZEHs. There has been a decrease in PV costs over the last several years and some industry experts expect this trend to continue, with the potential for costs to decrease to about half (based on $/watt) of what that they were when this demonstration took place.

The GSHPs used to heat and cool the ZEHs were also an important cost driver. GSHPs are typically most cost effective in locations where there are high winter heating and/or high summer cooling loads, as the systems can operate more efficiently in these locations compared to other systems. In addition, suitable soil conditions are critical for GSHPs to be cost effective, and must be evaluated prior to making a decision on this technology. GSHPs were included in these designs as a demonstration technology of interest by developer.

This project used small-scale renewable systems to achieve net zero design because the buildings were relatively small, and only one duplex was analyzed. If net zero energy on a community or site level was desired, a larger scale renewable energy project (e.g., ground mounted PV or geothermal-generated energy) could be more cost effective depending on the site characteristics.

One of the significant recurring maintenance costs was the monthly filter cleaning and annual filter replacement for the energy recovery ventilator. At almost $500 per year per house, this significantly reduced the benefit of the $1159 annual energy savings. Industry quotes indicate that energy recovery ventilator (ERV) replacement filters are available for $10-$50. It is not clear as to why Campbell Crossing had such high replacement costs, but lack of familiarity with the new technology could have been an issue.

7.2 COST ANALYSIS

The discounted cash flow analysis was conducted by summing the cash inflows (electricity savings, cost avoidance[4]) and outflows (capital costs, operating and maintenance costs, and debt costs) detailed in the following sections. Electricity costs were escalated and all costs discounted to 2012 dollars. The entire discounted cash flows for the 25- and 40-year study are located in the Final ESTCP Report.

Cash outflows included capital expenditures to construct the ZEHs (and associated debt charges) and to develop and execute the occupant interaction program. The loan amounts were considered outflows in the form of interest and principal payments at the end of each year. Electricity costs and fixed operating and maintenance costs were considered outflows, as was major equipment and component replacement.

LCC analysis (LCCA) study period is the number of years for which the cash flow analysis was completed. For this analysis, Campbell Crossing reported that the loan was taken in 2007 and therefore 2007 through the occupation date of 2010 were used as the construction period. For the 25-year scenario, years 2007-2009 were the planning and construction years and a 25-year occupation period began in 2010 and went through 2034. Therefore, for the 40-year study period, the occupation period was for 2010 through 2049 for a 43-year analysis period.

Electricity rate is the actual rate paid by Campbell Crossing in 2012. Electricity escalation rate was calculated using the U.S. Department of Commerce projections for electricity in the industrial sector for Census Region 3 (NIST, 2011).

Taxes for this project were not included in the analysis because Campbell Crossing is a PPV with the Army and does not pay taxes. Salvage value is the estimated value of an asset at the end of its useful life. According to Campbell Crossing, there is currently no mechanism in place for the valuation process of these privatized projects as it is early in the contract period. Therefore, no salvage value was used. The model developed for this analysis contains all the assumptions and calculations that were used in the analysis; the model is located in the final project report (Fowler, 2012).

Multiple cost scenarios were considered for this LCCA, including:

Individual Unit Scenario: Discounted cash flow was developed for each individual house. All parameters were consistent with the base scenario. Capital expenditures and O&M costs were

[4] Cost avoidance is due to ZEH metal roof life exceeding typical shingle roof life.

allocated evenly between the two houses and the actual energy consumption and production for each house was used. The study period was 25 years.

Energy Efficient Duplex Scenario: Independent of the net zero energy goal of this demonstration project, the objective was to investigate a more cost-effective, practical approach for the design and construction of housing with the intent of achieving a significant reduction in the energy required from the utility grid. To further evaluate progress toward this objective, an energy efficient duplex scenario was analyzed. The cost of PV equipment and the PV energy production was removed from the analysis. This scenario provides an estimate of the financial benefit of implementing the energy efficient features of the ZEH design. In addition, half of the commissioning costs were excluded from this scenario.

Energy Efficient Duplex without Solar Hot Water Scenario: This scenario evaluates the impact of the efficient envelope and the GSHP by replacing the solar water system with a domestic water system. The solar hot water system has high investment costs and efficiency can vary according to the characteristics of the system, use patterns of the occupants, and the building location. The solar hot water system costs were removed from the cost model. The differential energy usage was calculated using the measured electricity usage for the domestic water heater in the baseline home and the solar hot water heater electricity usage in the ZEH.

Energy Efficient Envelope Only Scenario: A scenario including only the energy efficient envelope and no additional equipment (i.e., no PV, no solar hot water, no GSHP, and no ERV) was also evaluated. GSHPs can also be an expensive technology, and depending on environmental conditions at a site, may not be cost effective compared to an efficient air source heat pump. For this scenario, estimated modeled energy usage of the air source heat pump was used instead of estimated GSHP energy use. Only the material cost differentials were included.

Minimum Acceptable Rate of Return Scenario: The Federal Energy Management Program (FEMP)-recommended discount rate was used for these analyses, because it is the recommended rate for use with government energy projects. As mentioned previously, military housing is unique in that it is operated by a PPV. Therefore, funding mechanisms are quite different. Under this scenario, the impact of the discount rate was investigated to mimic more closely how a private company would evaluate a similar project. Private companies use a minimum acceptable rate of return (MARR) as the metric for project acceptance; the investment opportunity is worthwhile if its rate of return is greater than the MARR. Campbell Crossing's MARR is proprietary; therefore, a range estimate was used based on typical values used by private companies. A lower bound of 10% was analyzed along with an upper bound of 15%. All other data remained the same; the study period was 25 years.

Impact of Reduced PV Costs Scenario: PV costs have decreased over the last several years. Industry experts expect this trend to continue. In addition, discussions with the PV vendor indicated that the 10% economies of scale factor provided by Campbell Crossing underestimates the cost reduction that would be realized with widespread implementation of PV. To further evaluate the economic impact on the project due to reduced PV costs, another scenario was analyzed using a cost decrease of 50% for the PV system.

Table 12 summarizes the LCCA scenario results for the first six scenarios.

Table 12. LCCA scenario results.

Cost Element	Base Case 40-year Analysis	Base Case 25-year Analysis	MARR 10%	MARR 15%	Individual Unit Scenario ZEH A	Individual Unit Scenario ZEH B
LCCA Lifetime	40	25	25	25	25	25
First Cost	$179,494	$179,494	$179,494	$179,494	$89,747	$89,747
Annual Energy Savings (kBtu)	8188	8188	8188	8188	4397	3791
Average Annual Savings	$2252	$2252	$2252	$2252	$1209	$1043
Average Annual Cost	$1395	$1252	$1252	$1252	$626	$626
Monthly Energy Savings (kBtu)	682	682	682	682	366	316
Monthly Energy Savings	$188	$188	$188	$188	$101	$87
Present Value of Annual Savings	$50,246	$38,702	$38,702	$38,702	$20,782	$17,920
$/kBtu Saved Annually	$0.55	$0.55	$0.55	$0.55	$0.51	$0.59
$/kBtu Saved Cumulatively	$22	$22	$22	$22	$20	$24
Simple Payback (years)	80	80	80	80	74	86
SIR	0.14	0.13	0.11	0.09	0.14	0.12
25-year net present value (NPV)	40 year NPV: ($298,847)	($257,657)	($212,586)	($201,079)	($127,397)	($130,259)

Table 12. LCCA Scenario Results (continued)

Cost Element	Energy Efficient Duplex	Energy Efficient Duplex (no Solar Hot Water)	Energy Efficient Envelope Only	Reduced PV Costs
LCCA Lifetime	25	25	25	25
First Cost	$72,741	$47,611	$30,331	$141,334
Annual Energy Savings (kBtu)	2505	2237	1800	8188
Average Annual Savings	$689	$615	$495	$2252
Average Annual Cost	$1090	$1018	$ -	$1179
Monthly Energy Savings (kBtu)	209	186	150	682
Monthly Energy Savings	$57	$51	$41	$188
Present Value of Annual Savings	$11,840	$10,574	$8507	$38,702
$/kBtu Saved Annually	$0.73	$0.53	$0.42	$0.43
$/kBtu Saved Cumulatively	$29	$21	$17	$17
Simple Payback (years)	106	77	61	63
SIR	0.10	0.13	0.21	0.16
25-year NPV	($99,711)	($67,005)	($28,686)	($205,861)

This analysis indicated that implementing ZEH at military installations would result in an increase in direct costs to the military. However, some of the non-quantifiable impacts are expected to be positive, and were considered qualitatively. Replacing grid electricity with renewable energy has benefits independent of information captured in this analysis, including:

- ***Indirect benefits*** associated with cost savings at the enterprise level could allow for a percent of the budget once appropriated to utility bills to be spent elsewhere.
- ***Contingent liability*** could be reduced because having a renewable energy system on-site could enhance energy security. The DoD could also be better positioned to comply with policies that require a certain amount of renewable energy and/or regulation GHGs.
- ***Future liability*** associated with electricity price volatility could also decrease.
- ***Internal intangible*** benefits could be seen in the form of organizational branding, because becoming more sustainable is viewed positively by the public and private sectors. As the organization communicates its efforts to be more socially responsible, its organizational image could benefit.
- ***External intangible*** benefits from displacing electricity from the grid with electricity from a PV system could include positive impacts on public health, worker safety, climate stabilization and air pollution.

With electricity costs of 7.9 ¢/kWh, design modifications to an already efficient home, such as the standard Campbell Crossing design are difficult to justify, as illustrated by LCCA results where no scenario evaluated was cost effective. Conditions that could enable a project to be cost effective include the following:

- Higher cost of energy, such as in California or eastern states.
- Lower technology costs. The 10% economy of scale factor used in this analysis may be conservative. With more widespread adoption of ZEH design and construction techniques in both the DoD and private sectors, material, technology, and installation costs may decrease even more in the future.
- Presence of rebates or other incentives. No incentives for using more efficient technologies were available for this project; however, many states, utilities, and municipalities offer incentives that can increase the economic practicality of a project.
- Improved home design. The design constraints in this project (the same floor area and layout as the standard Campbell Crossing design) may have hindered the cost effectiveness of the project.
- Alternative financing. Interest accrued over the 40-year loan term is more than twice the total loan amount. Cost-effectiveness would increase if all capital costs were paid in year one.

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8.0 IMPLEMENTATION ISSUES

Occupant engagement contributed to 15% less energy use in the baseline housing units compared to the Woodlands community. The ZEH housing units used on average 24% less energy than the baseline housing units, but did not achieve net zero energy during the study timeframe. The ZEH unit used 51% less water per person than the baseline unit. Low-flow water fixtures and other water efficiency strategies likely influenced this savings. There was no notable difference in emergency maintenance activities between the ZEH and baseline units; both the ZEH units and the baseline units had about the approximately the same level of emergency maintenance needs. The technologies in the ZEH units did require more preventative maintenance, specifically the ERV filter required regular cleaning and annual replacement. This preventative maintenance component resulted in monthly and annual costs that reduced the cost effectiveness.

Lessons were learned throughout each stage of this project: building design and construction, energy monitoring, and occupant interaction and behavior change.

8.1 BUILDING DESIGN AND CONSTRUCTION

- Design changes (e.g., smaller footprint, different layout) may result in additional opportunities for cost effective design.
- Design elements are not always carried through into construction.
- If design elements change after the building is modeled and the renewable energy system is sized, the projected energy use may not align with the selected renewable energy system.
- Verify that construction techniques to seal the building are completed as intended throughout building construction process so that infiltration is minimized.
- Achieving net zero energy may be more cost effective and practical in areas where cost of energy is higher, or where incentives for renewable energy or energy efficiency strategies are available.

8.2 MONITORING SYSTEM DESIGN AND INSTALLATION

- Design the metering plan with some overlap and/or correlated data points so it is possible to compare the total building energy use with an expected total energy use. Design circuits with only like loads if possible, and maximize the number of metered circuits serving electricity outlets in a building. Arrange sensors and monitoring system such that a single sensor or line failure has a minimum impact on the system as a whole. Designing the metering plan was successfully performed for this demonstration.
- Commission monitoring systems to enable useful and reliable conclusions regarding building performance. Commissioning activities include checking that panels are properly labeled; meters are measuring approximately the expected level and profile of energy use, and testing remote data collection process. Include monitoring system technical experts in the process to assist with troubleshooting as needed. This commissioning was successfully performed for this demonstration, although the

monitors could not be calibrated with the utility meters because the utility data were not available in real-time.

8.3 DATA COLLECTION AND ANALYSIS

- Back up local storage devices to allow data storage redundancy over the course of any extended network connectivity issues that may occur.
- Develop a robust and extensible system to store the building data and test the system with large amounts of trial data. Perform basic data validation as it is retrieved; compare data with expected use range and patterns. Use multiple data streams to provide multiple opportunities for checking data. This was successfully implemented on this demonstration project.
- If data collection and analysis occurs off site, ensure local assistance at the site will be available to perform troubleshooting as needed, and include them in monitoring system installation and commissioning so they are familiar with monitoring devices.

8.4 BEHAVIOR CHANGE/OCCUPANT INTERACTION

- Real-time energy feedback devices were the most useful to occupants in changing behavior.
- Engage occupants to provide the most useful information to reduce energy use. Responding to occupant feedback on the type of information they wished to see was specifically noted by occupants as something they appreciated.
- Saving money motivates behavior change. Even though occupants did not pay energy bills, lowering cost of energy was noted as a driver to reduce energy use.
- Large behavior changes may be required to achieve net zero energy, depending on the initial occupant preferences. One ZEH family preferred cooler indoor temperatures during the winter, leading to lower thermostat settings and lower energy use with minimal behavior change. Another ZEH family preferred warmer indoor temperatures; achieving the same lower energy use would have required a notable change in behavior.
- Focus behavior change on most impactful areas. At times, families focused on actions that had a relatively small impact on overall energy use, such as turning off lights or reducing laundry use, instead of larger impact areas such as lowering the thermostat to reduce heating energy use.

Findings that may be especially useful to inform future DoD policy include:

- Occupant feedback technologies, systems, and strategies have an impact on reducing energy use.
- ZEH designs may be more successful and cost-effective in areas such as California where energy costs are higher, renewable energy resource potential is greater, and designs are more adaptable.

9.0 TECHNOLOGY TRANSFER

Information regarding this project was presented at multiple conferences and technical meetings, including:

- U.S. Green Building Council's Greenbuild – Oct 2011
- West Coast Energy Management Congress – June 2011
- U.S. Green Building Council's Greenbuild Residential Summit – Nov 2009
- Fort Polk – August 2009
- Army Monthly Sustainability Information Exchange – May20 09
- Fort Lewis and Seattle Corps of Engineers (COE) District – February2009
- COE Net Zero Energy Conference – February2009
- Strategic Environmental Research and Development Program (SERDP)/ESTCP Annual Partners in Environmental Technology Technical Symposium and Workshop – December 2008
- Joint Services Environmental Management Conference – May 2008
- Headquarters (HQ) Army Residential Communities Initiative (RCI) conference – April 2008

End users that received direct training included the home occupants, Lend Lease, and Guantanamo Bay (GTMO) facilities personnel.

- Home occupant training development included orientation training where a home energy manual was developed as a resource for the families. Cards explaining unusual items such as the ShowerMinder and the high efficiency laundry equipment were also placed in the home as reminders of how the equipment can be used to help use less energy and water. Monthly energy reports provided detailed information on home energy consumption, comparisons to the other homes in the study and the neighborhood, and reminders on ways to save energy.
- The ESTCP team worked with Lend Lease to transfer knowledge on collecting, analyzing, and communicating the detailed monitoring data. The monitoring system was left in the homes and the goal was for the Lend Lease team to continue delivering more detailed energy data to the occupants. A methodology had been established for transferring data from the online database where it is stored to a workable spreadsheet. Training was provided regarding the data analysis and communication strategies used, however time and resource constraints have limited the Lend Lease team's ability to continue to provide the detailed monthly analysis. Lend Lease does plan to apply selected lessons learned regarding effective home design modifications and occupant engagement to the 38,000 homes they manage for the DoD and the 145,000 homes they manage worldwide.

- In FY 2012, personnel from GTMO approached the ESTCP team to learn more about the team’s experience with the Fort Campbell project as the GTMO personnel were implementing a similar ZEH design and monitoring project. ESTCP team shared monitoring system, design, and operation lessons learned and recommendations in support of a request for proposals that GTMO was submitting.

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APPENDIX A

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